CLAIMS

What is claimed is:

1. A method of timing recovery of symbols in a received signal, comprising the steps of:

(a) generating a sequence of samples from the received signal with a sample period and sample phase related to a symbol rate of the symbols;

(b) generating a phase error for a current sample from the sequence based on a gradient of a blind cost criterion of Bussgang-class cost functions;

(c) adjusting at least one of the sample period and sample phase based on the phase error such that a magnitude of the phase error is driven to a predetermined point; and

(d) repeating steps (a), (b), and (c) for subsequent samples.

2. The invention as recited in claim 1, wherein step (b) comprises the steps of:

(b1) calculating a blind cost error term based on the sample;

(b2) forming an approximation of a derivative of the received signal with respect to the sampling phase; and

(b3) combining the blind cost error term and the approximation to form the phase error.

3. The invention as recited in claim 1, wherein step (b) comprises the steps of:

(b1) calculating a blind cost error term based on the sample; and

(b2) forming an approximation of a derivative of the received signal with respect to the sampling phase.

4. The invention as recited in claim 3, further comprising the steps of (e) generating a quality measure for the received signal from the sequence; and wherein step (b1) further comprises the step of generating at least one other cost function error term based on a corresponding cost function criterion.

5. The invention as recited in claim 4, further comprising the steps of:

b3) selecting an error value, based on the quality measure, as either the blind cost error term or one cost function error term; and

b4) combining the error value with the approximation to form the phase error.

6. The invention as recited in claim 4, further comprising the steps of:

b3) selecting an error value, based on the quality level, as a weighted combination of the blind cost error term and the at least one other cost error term as the error value; and

b4) combining the error value with the approximation to form the phase error.

7. The invention as recited in claim 4, wherein, for step (b) the at least one cost function error term includes a least mean squares error term.

8. The invention as recited in claim 4, wherein, for step (b) the quality measure is based on at least one of a signal-to-noise ratio (SNR) of the received signal, SNR of a trellis decoder employed to detect each symbol, a number of symbols received, errors within a number of symbols received and detected, and vestigial sideband signal (VSB) framelock.

9. The invention as recited in claim 3, wherein, for step (b), either i) the blind cost criterion is a Constant Modulus (CM) cost criterion and the gradient is the CM algorithm or ii) the blind cost criterion is a Single-axis Constant Modulus (SA-CM) criterion and the gradient is a SA-CM algorithm.

10. The invention as recited in claim 9, wherein, for step (b) the CM cost criterion J_{CM} is expressed as:

$$J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2],$$

wherein ρ^2 is a dispersion constant, $y_n(\tau)$ is a discrete value representing the current sample generated at the sampling period, and τ represents the sampling phase; and

wherein the gradient is $dJ_{CM}/d\tau$ and is expressed as:

$$dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$$

wherein the derivative of the signal with respect to the sampling phase is $dy_n(\tau)/d\tau$ and a derivative of J_{CM} with respect to $y_n(\tau)$ is the blind cost error term determined as:

$$y_n(\tau)(\rho^2 - |y_n(\tau)|^2).$$

11. The invention as recited in claim 1, wherein, for step (b), the phase error is generated in accordance with a phase error calculation derived for a cost function error criterion having a corresponding cost function error term, the phase error calculation substituting the blind cost error term for the cost function error term.

12. The invention as recited in claim 11, for step (b) comprises the steps of:

(b1) calculating a blind cost error term for a current sample $y_n(\tau)$ and a blind cost error term for a previous sample $y_{n-1}(\tau)$,based on a gradient of a constant modulus (CM) cost criterion; and

(b2) combining the current and previous blind cost error terms with the current and previous samples generated at the sampling period to generate the timing phase error as:

$$y_n(\tau)y_{n-1}(\tau)\,((\rho^2 - |y_n(\tau)|^2) - (\rho^2 - |y_{n-1}(\tau)|^2))$$

where ρ^2 is a dispersion constant and τ represents the sampling phase.

13. The invention as recited in claim 1, wherein, for step (a) the received signal is demodulated from either a *m*-ary quadrature amplitude modulated (QAM) signal, a *m*-ary offset QAM signal, an *m*-ary phase-shift keyed modulated (*m*-ary PSK) signal, a vestigial sideband modulated (VSB) signal, a pulse amplitude modulated (PAM) signal, a signal modulated in accordance with a CCITT 802.11 standard, or a signal modulated in accordance with a V.27 standard.

14. The invention as recited in claim 1, wherein, for step (b), the Bussgang-class cost function is selected from either a Godard cost function, Benverniste-Goursat-Ruget cost function, or a Sato cost function.

15. The invention as recited in claim 1, wherein the method is embodied in a processor of an integrated circuit.

16. The invention as recited in claim 15, wherein the integrated circuit is embodied in a demodulator of a high definition television signal.

17. The invention as recited in claim 1, wherein, for step (a), the received signal is a

vestigial sideband (VSB) modulated signal, and, for step (b) the blind cost criterion is a Single-axis Constant Modulus (SA-CM) criterion and the gradient is a SA-CM algorithm.

18. The invention as recited in claim 1, wherein, for step (a), the received signal is a digital television signal having data encoding and modulation in accordance with an ATSC standard.

19. Apparatus for timing recovery of a symbol rate for symbols in a received signal, comprising:

a timing reference providing a reference signal;

a sample generator configured to generate a sequence of samples from the received signal with a sample period and sample phase based on the reference signal and related to the symbol rate;

a blind cost error term generator configured to generate a blind cost error term for a current sample of the sequence in accordance with a gradient of a blind cost criterion of Bussgang-class cost functions; and

a timing phase detector configured to generate a phase error for the current sample from the sequence and based on the blind cost error term;

wherein the timing reference modifies the reference signal based on the phase error to adjust at least one of the sample period and sample phase such that a magnitude of the phase error is driven to zero.

20. The invention as recited in claim 19, wherein the timing phase detector forms an approximation of a derivative of the received signal with respect to the sampling phase; and combines the blind cost error term and the approximation to form the phase error.

21. The invention as recited in claim 20, wherein the timing phase detector includes a filter having a delay chain receiving the sequence and a combiner, and the combiner forms the derivative of the signal with respect to the sampling phase by generating the difference between a previous sample from a corresponding delay of the delay chain and the current sample.

22. The invention as recited in claim 20, wherein the blind cost criterion is the Constant Modulus (CM) cost criterion and the gradient is the CM algorithm, and wherein the

blind cost error term is generated by:

ii) forming the gradient of the CM cost criterion as $dJ_{CM}/d\tau$ expressed as:

$$dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$$

wherein the CM cost criterion J_{CM} is defined as:

$$J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2]$$

in which ρ^2 is a dispersion constant, $y_n(\tau)$ is a discrete value representing the current sample generated at the sampling period, and τ represents the sampling phase; and

wherein the derivative of the received signal with respect to the sampling phase is $dy_n(\tau)/d\tau$ and a derivative of J_{CM} with respect to $y_n(\tau)$ is the blind cost error term given by

$$y_n(\tau)(\rho^2 - |y_n(\tau)|^2).$$

23. The invention as recited in claim 19, wherein the phase detector generates the phase error in accordance with a phase error calculation derived for a cost function error criterion having a corresponding cost function error term, the phase error calculation substituting the blind cost error term for the cost function error term.

24. The invention as recited in claim 23, wherein the blind-cost error term is based on a gradient of a constant modulus (CM) cost criterion for the current sample defined as

$$dJ_{CM}/d\tau = (dJ_{CM}/dy_n(\tau))dy_n(\tau)/d\tau,$$

wherein $J_{CM} = E[(\rho^2 - |y_n(\tau)|^2)^2]$ is the CM cost criterion, ρ^2 is a dispersion constant, $y_n(\tau)$ is a discrete value representing the current sample generated at the sampling period, τ represents the sampling phase, and $dy_n(\tau)/d\tau$ is a derivative of the received signal with respect to the sampling phase is $dy_n(\tau)/d\tau$, and a derivative of J_{CM} with respect to $y_n(\tau)$ is defined as the blind cost error term $e_{CMA}[n]$ given by

$$e_{CMA}[n]=y_n(\tau)(\rho^2 - |y_n(\tau)|^2); \text{ and}$$

wherein the timing phase detector combines a current blind cost error term $e_{CMA}[n]$ and a previous blind cost error term $e_{CMA}[n-1]$ with the current sample $y_n(\tau)$ and previous sample $y_{n-1}(\tau)$

to generate the timing phase error as:

$$y_n(\tau)y_{n-1}(\tau)\left((\rho^2 - |y_n(\tau)|^2) - (\rho^2 - |y_{n-1}(\tau)|^2)\right)$$

25. The invention as recited in claim 19, wherein the sample generator comprises an analog-to-digital (A/D converter) configured to generate a sequence of discrete values from the received signal.

26. The invention as recited in claim 25, wherein the timing reference is an oscillator coupled to the A/D converter, and the A/D converter generates the sequence of discrete values so as to convert the received signal to the sequence of samples with the sampling phase and the sampling period.

27. The invention as recited in claim 25, wherein the sample generator further comprises an interpolator coupled to the A/D converter and coupled to the timing reference generator, wherein the interpolator is configured to adjust the sequence of discrete values from the A/D converter to form the sequence of samples with the sampling period and the sampling phase.

28. The invention as recited in claim 25, wherein the received signal is demodulated from either a *m*-ary quadrature amplitude modulated (QAM) signal, a *m*-ary offset QAM signal, an *m*-ary phase-shift keyed modulated (*m*-ary PSK) signal, a vestigial sideband modulated (VSB) signal, a pulse amplitude modulated (PAM) signal, a signal modulated in accordance with a CCITT 802.11 standard, or a signal modulated in accordance with a V.27 standard.

29. The invention as recited in claim 19, further comprising 1) a signal quality processor generating a signal quality measure (SQM) signal, and 2) at least one cost function error generator, each cost function error generator configured to generate a cost function error term with a corresponding cost function criterion.

30. The invention as recited in claim 19, further comprising a multiplexer selecting either the blind cost error term or at least one cost function error term based on the SQM signal; and

wherein the timing phase detector, based on the SQM signal, either i) provides the phase error generated with the blind cost error term or ii) provides the phase error based on the selected

cost function error term from the multiplexer.

31. The invention as recited in claim 29, further comprising a weighting mechanism circuit, the weighting mechanism circuit forming, based on the SQM signal, a weighted combination of i) the blind cost error term with ii) the at least one cost function error term, and wherein the timing phase detector, based on the SQM signal, generates the phase error with the weighted combination.

32. The invention as recited in claim 29, wherein the SQM signal is based on at least one of a signal-to-noise ratio (SNR) of the received signal, SNR of a trellis decoder employed to detect each symbol, a number of symbols received, errors within a number of symbols received and detected, and ATSC frame synchronization acquisition.

33. The invention as recited in claim 19, wherein the blind cost error generator is included in an adaptive equalizer, the blind cost error generator forming the blind cost error term to update equalizer coefficients.

34. The invention as recited in claim 19, wherein the Bussgang-class cost function is selected from either a Godard cost function, Benverniste-Goursat-Ruget cost function, or a Sato cost function.

35. The invention as recited in claim 19, wherein the apparatus is embodied in an integrated circuit.

36. The invention as recited in claim 35, wherein the apparatus is embodied in a demodulator of a high definition television signal.

37. The invention as recited in claim 19, wherein the received signal is a vestigial sideband (VSB) modulated signal, and the blind cost criterion is a Single-axis Constant Modulus (SA-CM) criterion and the gradient is a SA-CM algorithm.

38. The invention as recited in claim 19, wherein the received signal is a digital television signal having data encoding and modulation in accordance with an ATSC standard.

39. A computer-readable medium having stored thereon a plurality of instructions, the plurality of instructions including instructions which, when executed by a processor, cause the

processor to implement a method for timing recovery of symbols in a received signal, the method comprising the steps of:

(a) generating a sequence of samples from the received signal with a sample period and sample phase related to a symbol rate of the symbols;

(b) generating a phase error for a current sample from the sequence based on a gradient of a blind cost criterion of Bussgang-class cost functions;

(c) adjusting at least one of the sample period and sample phase based on the phase error such that a magnitude of the phase error is driven to zero; and

(d) repeating steps (a), (b), and (c) for subsequent samples.

40. The invention as recited in claim 39, wherein step (b) comprises the steps of:

(b1) calculating a blind cost error term based on the sample;

(b2) forming an approximation of a derivative of the received signal with respect to the sampling phase; and

(b3) combining the blind cost error term and the approximation to form the phase error.